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Acute Lower Extremity Running Kinematics After a Hamstring Stretch

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Context: Limited passive hamstring flexibility might affect kinematics, performance, and injury risk during running. Preactivity static straight-leg raise stretching often is used to gain passive hamstring flexibility.

Objective: To investigate the acute effects of a single session of passive hamstring stretching on pelvic, hip, and knee kinematics during the swing phase of running.

Design: Randomized controlled clinical trial.

Setting: Biomechanics research laboratory.

Patients or Other Participants: Thirty-four male (age = 21.2 ± 1.4 years) and female (age = 21.3 ± 2.0 years) recreational athletes.

Intervention(s): Participants performed treadmill running pretests and posttests at 70% of their age-predicted maximum heart rate. Pelvis, hip, and knee joint angles during the swing phase of 5 consecutive gait cycles were collected using a motion analysis system. Right and left hamstrings of the intervention group participants were passively stretched 3 times for 30 seconds in random order immediately after the pretest. Control group participants performed no stretching or movement between running sessions.

Main Outcome Measure(s): Six 2-way analyses of variance to determine joint angle differences between groups at maximum hip flexion and maximum knee extension with an α level of .008.

Results: Flexibility increased between pretest and posttest in all participants ($F_{1,30} = 80.61$, $P < .001$). Anterior pelvic tilt ($F_{1,30} = 0.73$, $P = .40$), hip flexion ($F_{1,30} = 2.44$, $P = .13$), and knee extension ($F_{1,30} = 0.06$, $P = .80$) at maximum hip flexion were similar between groups throughout testing. Anterior pelvic tilt ($F_{1,30} = 0.69$, $P = .41$), hip flexion ($F_{1,30} = 0.23$, $P = .64$), and knee extension ($F_{1,30} = 3.38$, $P = .62$) at maximum knee extension were similar between groups throughout testing. Men demonstrated greater anterior pelvic tilt than women at maximum knee extension ($F_{1,30} = 13.62$, $P = .001$).

Conclusions: A single session of 3 straight-leg raise hamstring stretches did not change pelvis, hip, or knee running kinematics.

Key Words: straight-leg raises, flexibility

Key Points

- Pelvis, hip, and knee kinematics during running did not change with a single session of 3 hamstring stretches.
- Hamstring flexibility increased in both groups between pretest and posttest, probably because an active warmup was performed before data collection.

Running is popular as a recreational and competitive sport of its own and as a necessary form of locomotion within other sports. Given that more than 7 million runners reported running at least 100 days in 2006,[1] investigating factors contributing to its performance is important. The flexibility of muscle groups involved in running must be considered.[2,3] The concern with lower extremity flexibility stems from its potential influence on various aspects of running. Limited lower extremity flexibility can result in changes in the dynamic range of motion (ROM) used, biomechanics,[4–8] injury risk,[9] and performance.[6,10–14] Although many researchers have studied flexibility, the assessment of flexibility, and the various techniques used to increase flexibility, conflicting results have led to confusion about optimal techniques.[4,15,16]

Active and passive flexibility can be measured in either stiffness (increased resistance to deformation of a muscle)[4,17–20] or degrees of ROM available at a joint or group of joints due to elongation of muscle fibers and connective tissues.[2,3,9,16,21–28] The flexibility of muscle groups such as the hamstrings is manipulated regularly through methods such as active warmup[15,29–31] and stretching in fitness and sport to increase flexibility, with the objective of preventing injury[9] and improving performance.[15,30,31] Despite the debate over the effectiveness of stretching, athletes regularly include this as part of their preactivity protocols. Static, ballistic, proprioceptive neuromuscular facilitation (PNF), and dynamic stretching techniques are used commonly in athletics. Although all 4 stretching methods can increase hamstring flexibility,† static stretches remain the most widely used because they are easy to understand and implement.[40] Researchers have found that static stretching causes a viscoelastic response of the muscle-tendon unit.[31] This vis-

* *References 2, 3, 10, 15, 16, 21–24, 26, 29, 30, 32–36.*
† *References 2, 12, 16, 21–24, 26, 32, 34–39.*

coelastic response results in passive tension reduction for any given length of the tissue, allowing increased flexibility to be achieved.[17,31] Yet the increased flexibility does not necessarily equate to a permanent decrease in passive muscle stiffness, indicating only a temporary decrease in tension[4] or increased subjective stretch tolerance.[4,24] Most studies about the effectiveness of stretching for increasing flexibility include a protocol performed over several days or weeks.[2,3,16,24,26,31] However, researchers have demonstrated that a single session of static or PNF hold-relax hamstring stretching with no additional activity results in increased flexibility for approximately 3 minutes[24,26] and even up to 24 hours.[29] The authors[24,26,29,38,39] of these investigations concluded that athletes should engage in activity immediately after a single session of static or PNF hamstring stretching to take advantage of the full benefits of the increased flexibility.

Increased stiffness affecting the quality and quantity of ROM available to perform functional tasks can alter events within the kinetic chain in coordinated actions such as running. For instance, hamstring muscles that are tight enough to cause compensations are at a disadvantage in absorbing energy while lengthening[41] and producing force while shortening.[37,41] Increasing flexibility in such cases theoretically would enable greater force to be absorbed when lengthening, making more potential energy available to produce force during shortening.[37,41] In addition, Faulkner[41] reported that patients who have cerebral palsy and limited flexibility of the hamstring muscles have less available knee extension during the terminal swing phase of gait, which decreases stride length.[42] Simulated hamstring shortening has been shown to pull inferiorly on the posterior pelvis.[43] An inferior pull on the posterior pelvis decreases lumbar lordosis.[44,45] Erector spinae fatigue develops, and forward trunk lean increases.[46] This altered posture might produce low back pain.[47] In addition, increased demand on the quadriceps to overcome the loss of knee extension ROM when the hip is flexed during terminal swing phase might lead to patellar tendinitis[48] and patellofemoral pain syndrome.[49] Investigators have documented that single and repetitive sessions of passive static hamstring stretching increase flexibility[‡] and decrease passive muscle stiffness.[4] However, we do not know whether the ROM needs to be functional and whether kinematic compensations would be corrected with temporary flexibility improvements. The lack of research on this adds to the uncertainty of the effects of stretching in reducing the risk of injury.

Therefore, the purpose of our study was to investigate the acute effects of a single session of passive static hamstring stretching on running biomechanics in recreational athletes. We hypothesized that participants who received a passive, static hamstring stretch would have increased anterior pelvic tilt, hip flexion, and knee extension during the swing phase of running at maximum hip flexion and maximum knee extension.

METHODS

Participants

We recruited 34 male (age $=21.2\pm1.4$ years) and female (age $=21.3\pm2.0$ years) recreational athletes as volunteer participants. The control group ($n=16$) consisted of 7 women (age $=21.3\pm2.6$ years, height $=164.9\pm4.9$ cm, mass $=58.8\pm3.7$ kg) and 9 men (age $=21.2\pm1.1$ years, height $=178.9\pm6.9$ cm, mass $=81.3\pm14.1$ kg). The intervention group ($n=18$) consisted of 10 women (age $=21.5\pm1.7$ years, height $=165.4\pm5.9$ cm, mass $=62.2\pm8.5$ kg) and 8 men (age $=21.3\pm1.6$ years, height $=179.1\pm6.0$ cm, mass $=77.2\pm4.9$ kg). We defined *recreational athlete* as a person engaging in moderate-intensity to vigorous-intensity exercise for 20 minutes or longer at least 3 times each week for a minimum of 3 months. Exclusion criteria were a history of lower extremity surgery, injury that prevented running within the 3 months before the investigation, and neuromuscular conditions known to affect muscular strength and flexibility. All participants provided written informed consent, and the Illinois State University Institutional Review Board approved this study.

Instrumentation

Eleven reflective motion-analysis markers (Vicon Motus Gait Marker Set; Vicon Motion Systems, Inc, Centennial, CO) in conjunction with an optical capture system (Peak Motus version 9.0; Vicon Motion Systems, Inc) with 6 infrared cameras (Vicon MX-3; Vicon Motion Systems, Inc) operating at 200 Hz were used to capture pelvic tilt, hip flexion, and knee extension angles during running. To ensure that all participants were running with similar intensity, heart rate was monitored with a heart monitor (model CE 0537; Polar Electro Oy, Kempele, Finland). A clear plastic goniometer with a 31.25-cm axis and 12.75-cm diameter protractor that reads 0° to 360° in 1° increments was used to measure prestretch and poststretch hamstring flexibility.

Procedures

Two examiners (A.D.H. = *first examiner,* examiner who was not an author = *second examiner*), who remained consistent in their roles, were involved in all data collection. All participants attended 1 testing session in a biomechanics laboratory setting. They received a written explanation of the testing procedures and could ask questions. Reflective motion-analysis markers were placed bilaterally at the anterior-superior iliac spine,[50] midpoint between the posterior-superior iliac spines,[50] greater trochanter of the femur,[19] lateral condyle of the femur,[50] lateral malleolus,[19] and head of the fifth metatarsal[19] (Figure 1). To maintain consistency, the first examiner placed all anatomical markers on each participant.

After marker placement, each participant completed 1 5-second standing calibration trial to determine pelvic tilt before flexibility testing to enable calculations of pelvic tilt during running. *Pelvic tilt* was defined as rotation of the pelvic segment around the mediolateral axis parallel with the ground. Inferior movement of the anterior-superior iliac spine and superior movement of the posterior-superior iliac spines as the pelvis rotates around the mediolateral axis, or anterior pelvic tilt, was assigned a positive value. *Hip flexion-extension* was defined as the angle formed by the ipsilateral pelvis and thigh segments and its rotation about the mediolateral axis. Positive, increasing values of hip joint angles defined *flexion,* and negative, decreasing values of hip joint angles defined *extension.*[50] *Knee extension* was defined as the angle formed between the thigh and shank segments, with full extension equaling 180°.

Data Collection. Hamstring flexibility was measured bilaterally for all participants using the passive straight-leg raise (SLR) test. While the participant lay supine with the test hip in neutral rotation and the contralateral hip and knee stabilized

‡ *References 2, 3, 12, 16, 22–24, 26, 29, 32, 34–37.*

Figure 1. Marker placement. The midpoint between the posterior-superior iliac spines is not pictured.

in extension with neutral rotation, the first examiner passively flexed the test hip to the first point of tissue resistance, which was the position at which the participant either could no longer maintain the spine and pelvis in neutral position or reported discomfort. This position was held only for the hip flexion angle to be measured by the second examiner. To measure the angle, this examiner, who was positioned beside the table, placed the goniometer fulcrum on the greater trochanter of the test hip. The stationary arm of the goniometer was aligned parallel with the participant's trunk, and the movable arm was aligned with an imaginary line extending through the midline of the lateral thigh[49,51] and through the lateral knee joint line and ending with the lateral malleolus. We extended this line to the lateral malleolus to help ensure that full knee extension was maintained throughout the passive SLR test. After the prestretch SLR test, participants rested for approximately 3 minutes to decrease any possible effects on flexibility[24] and to lower their heart rates. According to Bandy and Irion,[21] flexibility was unlikely to remain increased after the SLR test because of the short time the position was held. At the end of the rest period, participants' resting heart rates were recorded so we could calculate 70% of their age-predicted maximum heart rates, as determined by the Karvonen method.[52] Investigators[53] have found that reproducibility of kinematic running data probably is not compromised when participants run within 10% of their preferred stride frequency. We believed that preferred stride frequency would be attained more easily by having our participants run with intensity rather than by normalizing speed because we included recreational athletes who do not necessarily have an exercise background specific to running.

Participants wore their own running shoes for the prestretch and poststretch running data collections. They performed a short treadmill warmup of approximately 3 minutes at a nonfatiguing, moderately intense speed until reaching the predetermined heart rate to increase the reproducibility and symmetry of kinematic data.[53] Fifteen seconds of kinematic data collection began as soon as each participant orally notified the examiners that the heart monitor displayed the previously determined heart rate. The poststretch running kinematic data collection was conducted using the same procedures.

Intervention. After collection of baseline running kinematic data, the control group rested for 4 minutes with no stretch or movement. Four minutes was the approximate time the intervention group needed to undergo the stretching protocol. The first examiner used a passive SLR to stretch the hamstrings of the intervention group (Figure 2). Participants lay supine on a standard treatment table with the test hip in neutral rotation and the contralateral hip and knee stabilized in extension with neutral rotation. The first examiner passively flexed the hip until the first point of tissue resistance, which was the stretch position at which the participant either could no longer maintain the spine and pelvis in neutral position or reported discomfort. This procedure was conducted 3 times for 30 seconds each and included 15 seconds of rest between stretches. The order of stretching the right and left legs was randomized. Immediately after the 4-minute rest or stretching intervention, poststretch bilateral hamstring flexibility was measured using the passive SLR test. To avoid losing any potential effects of the stretching protocol, participants returned to the treadmill to complete the poststretch running data collection. The control group participants also returned to the treadmill for data collection immediately after the post-SLR test because the test was unlikely to increase flexibility.

Data Processing

Five consecutive gait cycles of each participant's bilateral kinematic data were selected from the 15 seconds of data collected. The gait cycles were selected based on having clear, uninterrupted readings from each reflective marker throughout the portion of the swing phase we evaluated. Pelvic tilt, hip flexion, and knee extension angles were identified bilaterally at maximum hip flexion and maximum knee extension of the swing phase for each participant.

Statistical Analysis

Data collected for dependent variables from the right and left sides were averaged, as researchers[51,54] have suggested. Our dependent variable joint angle data then were analyzed using 6 separate 2-way analyses of variance (ANOVAs) with repeated measures to determine differences between pretest and posttest running sessions. Joint angle data were analyzed with a 2□2□2 design to determine sex by intervention interactions over time. Because multiple tests were conducted, α_1 was adjusted using a standard-version Bonferroni correction (<.05/6 or <.008) to guard against type I error. Baseline standing pelvic tilt angle data were analyzed with a 2×2 ANOVA to determine sex by intervention interactions, and α_2 was set at <.05. Two additional 2×2×2 ANOVAs with repeated measures were conducted to determine sex by intervention interactions over time for tread-

Figure 2. Straight-leg raise stretching protocol.

mill speed and flexibility. Because multiple tests were conducted, α_3 was adjusted using a standard-version Bonferroni correction (<.05/4 or <.01) to guard against type I error. All statistical analyses were conducted with SPSS (version 14.0; SPSS Inc, Chicago, IL).

RESULTS

Flexibility

Changes in flexibility did not exhibit an intervention by time interaction ($F_{1,30}=4.17$, $P=.05$) (Table 1). Changes in flexibility also did not exhibit a time by sex interaction ($F_{1,30}=0.001$, $P=.97$). We also did not find a sex by intervention interaction over time ($F_{1,30}=3.56$, $P=.07$). However, the analysis did reveal that flexibility for all participants increased between the pretests and posttests ($F_{1,30}=80.61$, $P<.001$). No main effects were found for intervention group ($F_{1,30}=2.52$, $P=.12$), sex ($F_{1,30}=8.59$, $P=.01$), or intervention group and sex ($F_{1,30}=0.20$, $P=.65$).

Treadmill Speed

Analysis of treadmill running speed based on 70% of the age-predicted maximum heart rate did not reveal an interaction between intervention and time ($F_{1,30}=0.28$, $P=0.60$) or between time and sex ($F_{1,30}=3.72$, $P=0.06$) (Table 1). Treadmill speed increased between the pretests and posttests for all participants ($F_{1,30}=22.44$, $P<.001$). No main effects were found for intervention ($F_{1,30}=0.07$, $P=.79$), sex ($F_{1,30}=3.30$, $P=.08$), or intervention group and sex ($F_{1,30}=0.55$, $P=.46$).

Standing Pelvic Tilt

Standing pelvic tilt angle was not different between the intervention and control groups ($F_{1,30}=0.03$, $P=.86$) or between men and women ($F_{1,30}=0.05$, $P=.82$) (Tables 2 and 3). We found no sex by intervention interaction ($F_{1,30}=2.99$, $P=.09$). Results for standing pelvic tilt are given in Tables 2 and 3 to aid in comparisons with pelvic tilt at maximum hip flexion and maximum knee extension.

Joint Angles at Maximum Hip Flexion

We did not find an intervention by time interaction ($F_{1,30}=0.73$, $P=.40$) or a time by sex interaction ($F_{1,30}=0.22$, $P=.64$) for pelvic tilt at maximum hip flexion (Table 2). We found no difference between the pretest and posttest running sessions ($F_{1,30}=0.86$, $P=.32$). No sex by intervention interaction over time was found ($F_{1,30}=1.13$, $P=.30$). We also found no main effects for intervention ($F_{1,30}=0.88$, $P=.36$), sex ($F_{1,30}=8.34$, $P=.01$), or intervention and sex ($F_{1,30}=0.07$, $P=.79$).

We did not find a time by intervention group interaction ($F_{1,30}=2.44$, $P=.13$) or a sex by time interaction ($F_{1,30}=0.01$, $P=.93$) for maximum hip flexion (Table 2). We found no difference between the pretest and posttest running sessions ($F_{1,30}=0.44$, $P=.51$). No sex by intervention interaction over time for maximum hip flexion was found ($F_{1,30}=0.04$, $P=.85$). In addition, no main effects were exhibited for intervention ($F_{1,30}=0.73$, $P=.40$), sex ($F_{1,30}=0.13$, $P=.73$), or intervention and sex ($F_{1,30}=1.17$, $P=.29$).

Table 1. Hamstring Flexibility and Treadmill Speed (Mean ± SD)

Variable	Prestretch			Poststretch		
	Men	Women	Total	Men	Women	Total
Hamstring flexibility,[a] °						
Stretch	88.9 ± 11.5	105.9 ± 22.7	98.4 ± 20.0	93.3 ± 10.7	112.0 ± 23.5	103.6 ± 20.8
Control	83.0 ± 5.8	97.0 ± 13.3	89.1 ± 11.8	87.2 ± 5.7	99.4 ± 13.7	92.5 ± 11.5
Total	85.8 ± 9.1	102.2 ± 19.4	94.0 ± 17.1	90.0 ± 8.7	106.8 ± 20.6	98.4 ± 17.7[b]
Treadmill speed, m/s						
Stretch	2.9 ± 0.4	2.8 ± 0.6	2.9 ± 0.5	3.2 ± 0.4	2.9 ± 0.6	3.0 ± 0.5
Control	3.1 ± 0.4	2.7 ± 0.3	2.9 ± 0.4	3.3 ± 0.5	2.9 ± 0.4	3.1 ± 0.5
Total	3.0 ± 0.4	2.8 ± 0.5	2.9 ± 0.5	3.3 ± 0.4	2.9 ± 0.5	3.1 ± 0.5[b]

[a] Values for hamstring flexibility are reported in degrees of range of motion.

[b] Poststretch measurement was different from prestretch measurement ($P \leq .001$).

Table 2. Pelvis, Hip Joint, and Knee Joint Angles at Maximum Hip Flexion (Mean ± SD)

Joint Angle	Maximum Hip Flexion						Baseline Calibration		
	Prestretch			Poststretch			Standing[a]		
	Men	Women	Total	Men	Women	Total	Men	Women	Total
Pelvic tilt, °									
Stretch	9.0 ± 4.3	5.1 ± 5.5	6.8 ± 5.3	9.4 ± 3.9	4.8 ± 4.4	6.8 ± 4.7	6.4 ± 6.2	8.8 ± 5.0	7.7 ± 5.5
Control	8.1 ± 6.7	2.0 ± 4.3	5.4 ± 6.4	8.2 ± 5.4	3.8 ± 4.5	6.3 ± 5.4	8.9 ± 3.0	5.7 ± 3.6	7.5 ± 3.6
Total	8.5 ± 5.5	3.8 ± 5.1	6.2 ± 5.8	8.8 ± 4.7	4.4 ± 4.3	6.6 ± 5.0	7.7 ± 4.8	7.5 ± 4.6	7.6 ± 4.6
Hip flexion, °									
Stretch	29.9 ± 6.8	32.8 ± 6.3	31.5 ± 6.5	29.4 ± 6.3	32.0 ± 6.3	30.8 ± 6.3			
Control	32.6 ± 6.4	31.1 ± 2.8	31.9 ± 5.0	34.1 ± 4.2	32.8 ± 6.3	33.6 ± 5.1			
Total	31.3 ± 6.5	32.1 ± 5.1	31.7 ± 5.8	31.9 ± 5.7	32.3 ± 6.1	32.1 ± 5.8			
Knee extension, °									
Stretch	101.4 ± 14.6	90.4 ± 6.9	95.3 ± 12.0	102.1 ± 12.7	87.5 ± 10.6	94.0 ± 13.5			
Control	101.2 ± 11.0	108.9 ± 6.5	104.6 ± 9.9	99.8 ± 13.1	106.5 ± 12.8	102.7 ± 13.0			
Total	101.3 ± 12.4	98.0 ± 11.5	99.7 ± 11.9	100.9 ± 12.6	95.3 ± 14.7	98.1 ± 13.8			

[a] Standing pelvic tilt values are included to aid in comparison of pelvic tilt angles.

Table 3. Pelvis, Hip Joint, and Knee Joint Angles at Maximum Knee Extension (Mean ± SD)

Joint Angle	Maximum Knee Extension						Baseline Calibration		
	Prestretch			Poststretch			Standing[a]		
	Men	Women	Total	Men	Women	Total	Men	Women	Total
Pelvic tilt, °									
Stretch	10.2 ± 3.8	3.9 ± 4.7	6.7 ± 5.3	10.4 ± 3.2	2.1 ± 7.2	5.8 ± 7.0	6.4 ± 6.2	8.8 ± 5.0	7.7 ± 5.5
Control	9.1 ± 6.0	2.8 ± 5.4	6.3 ± 6.4	8.5 ± 6.1	4.1 ± 4.2	6.6 ± 5.7	8.9 ± 3.0	5.7 ± 3.6	7.5 ± 3.6
Total	9.6 ± 5.0	3.5 ± 4.9[b]	6.5 ± 5.7	9.4 ± 4.8	2.9 ± 6.0[b]	6.2 ± 6.3	7.7 ± 4.8	7.5 ± 4.6	7.6 ± 4.6
Hip flexion, °									
Stretch	22.9 ± 3.9	20.1 ± 6.1	21.3 ± 5.3	23.7 ± 4.7	18.9 ± 5.9	21.1 ± 5.8			
Control	25.2 ± 4.2	20.33 ± 3.7	23.1 ± 4.6	24.3 ± 5.6	22.0 ± 5.2	23.3 ± 5.4			
Total	24.1 ± 4.1	20.2 ± 5.1	22.1 ± 5.0	24.0 ± 5.1	20.2 ± 5.7	22.1 ± 5.6			
Knee extension, °									
Stretch	170.6 ± 4.3	169.1 ± 5.7	169.8 ± 5.1	169.8 ± 6.0	168.0 ± 5.6	168.8 ± 5.7			
Control	170.4 ± 4.9	170.0 ± 4.6	170.2 ± 4.6	167.9 ± 9.1	169.3 ± 4.3	168.5 ± 7.2			
Total	170.5 ± 4.5	169.5 ± 5.2	170.0 ± 4.8	168.8 ± 7.6	168.6 ± 5.0	168.7 ± 6.3			

[a] Standing pelvic tilt values are included to aid in comparison of pelvic tilt angles.

[b] Main effect of sex revealed that pelvic tilt in female participants (3.2° ± 1.2°) was different from pelvic tilt in male participants (9.5° ± 1.2°) ($P = .001$).

We did not find an intervention by time interaction ($F_{1,30}$ =0.06, P=.80) or a sex by time interaction ($F_{1,30}$=0.51, P=.48) for knee extension at maximum hip flexion (Table 2). We found no difference between the pretest and posttest running sessions ($F_{1,30}$=0.83, P=.37). We did not find a sex by intervention interaction over time for knee extension at maximum hip flexion ($F_{1,30}$=0.13, P=.72). In addition, no main effects were exhibited for intervention ($F_{1,30}$=6.09, P=.02), sex ($F_{1,30}$=.63, P=.43), or intervention and sex ($F_{1,30}$=8.03, P=.01).

Joint Angles at Maximum Knee Extension

We did not find an interaction between intervention and time ($F_{1,30}$=0.69, P=.41) or between time and sex ($F_{1,30}$=0.04, P=.94) for pelvic tilt at maximum knee extension (Table 3). We found no difference between the pretest and posttest running sessions ($F_{1,30}$=0.10, P=.75). We found no interaction between sex and intervention over time ($F_{1,30}$=2.05, P=.16). We also found no main effects for intervention ($F_{1,30}$=0.09, P=.76) or intervention and sex ($F_{1,30}$=0.32, P=.58). Sex exhibited a main effect for pelvic tilt at maximum knee extension ($F_{1,30}$=13.62, P=.001).

We did not find a time by intervention interaction ($F_{1,30}$=0.23, P=.64) or a sex by time interaction ($F_{1,30}$=0.09, P=.77) for hip flexion at maximum knee extension (Table 3). We found no difference between the pretest and posttest running sessions ($F_{1,30}$=0.03, P=.86). No interaction between intervention and sex over time was found for hip flexion at maximum knee extension ($F_{1,30}$=3.41, P=.08). In addition, no main effects were exhibited for intervention ($F_{1,30}$=0.88, P=.36), sex ($F_{1,30}$=5.08, P=.03), or intervention and sex ($F_{1,30}$=0.01, P=.93).

We did not find a time by intervention interaction ($F_{1,30}$=3.38, P=.62) or a sex by time interaction ($F_{1,30}$=0.30, P=.59) for maximum knee extension angles (Table 3). We found no difference between the pretest and posttest running sessions ($F_{1,30}$=3.38, P=.08). No interaction between intervention and sex over time was found ($F_{1,30}$=0.66, P=.42). In addition, no main effects were exhibited for intervention ($F_{1,30}$<0.001, P>.99), sex ($F_{1,30}$=0.09, P=.76), or intervention and sex ($F_{1,30}$=0.30, P=.59).

DISCUSSION

Flexibility

An increase in hamstring flexibility was observed in all participants. This observation is similar to observations by other authors who have found that a single session of static stretching without activity immediately before or after is an effective method of increasing hamstring flexibility.[24,29,38,39] DePino et al[24] noted that flexibility was increased for at least 3 minutes after a single session of 4 30-second self-stretches. de Weijer et al[29] observed that participants receiving a single session of hamstring stretches with or without an active warmup demonstrated increased flexibility for at least 24 hours. They also reported that participants engaging in an active warmup followed by a stretch, as our participants did, demonstrated increased flexibility for at least 24 hours. Zakas et al[38] found that adolescent soccer players who completed a stretching protocol with or without a warmup experienced increased ROM at all joints measured. In addition, Magnusson et al[39] noted that male recreational athletes who performed 3 stretching maneuvers also experienced an increase in joint ROM. Although all our participants demonstrated increased flexibility, not all participants received a session of SLR hamstring stretching. Therefore, we cannot conclude definitively that the stretching session was the only contributing factor to the increased flexibility.

The stretching methods we used were similar to but differed from those of previous researchers[21,24,29,34,55] who have found increases in flexibility after a stretching protocol. For example, DePino et al[24] observed increased ROM in male collegiate military cadets lacking at least 20° of knee extension as measured by the active knee extension (AKE) test after they completed 4 self-imposed standing hamstring stretches for 30 seconds. Each stretch included holding the pelvis in relative anterior rotation,[24] which has been shown to be important when stretching hamstring muscles.[55] We did not control for adding relative anterior pelvic rotation. Participants lacking at least 15° of AKE in the study by de Weijer et al[29] completed 3 supine hamstring stretches with the hip flexed to 90°. Knee extension was increased passively at 5°/s and held for 15 seconds before additional force was applied, to correspond with the new perception of maximum pain tolerance. This new position was held for 30 seconds.[29] Our participants may have reported discomfort before the passive SLR reached the first point of tissue resistance, which would decrease greatly the probability that the first tissue resistance felt was not enough to produce increased hamstring flexibility. Similar to de Weijer et al,[29] other researchers[21,34] have found that participants lacking at least 20° of passive knee extension demonstrated an increase in hamstring flexibility using a protocol including at least 30 seconds of static stretching. In addition, we do not know whether participants like ours who are not lacking at least 15° of AKE[24,29] or 20° of passive knee extension[21,34] also would experience increased flexibility after undergoing a stretching protocol. Zakas et al[38] noted that each stretch was conducted 3 times and held for 15 seconds. However, they did not describe the stretching method used. Magnusson et al[39] applied 3 passive knee extension stretches for 90 seconds each to only the left leg with participants seated upright. They used a stretching protocol that was 60 seconds longer than that used in our study, which might not be practical for athletes under preactivity time constraints.[39] Because researchers[21,34] have found no difference in hamstring flexibility changes when the stretch was maintained more than 30 seconds, our stretch duration probably did not contribute to the differing results. The differences in our participants[21,24,29,34] and in pelvic rotation[24,55] probably had a greater influence on the results.

We anticipated that hamstring flexibility might increase moderately for all participants. However, we did not predict that all participants would demonstrate increased flexibility between the pretest and posttest measurements. Taylor et al[31] proposed that connective tissues passively lengthen as muscle fibers actively shorten. This mechanism probably is similar to what occurs during the lengthening[41] phases of hamstring activity during the swing phase of running. As the knee extends, the hamstring muscle group is active in controlling[56] its lengthening[41] and transfer of energy from the swinging limb to the pelvis.[42,43] Lengthening of hamstring muscle fibers combined with the resistance to posterior rotation of the pelvis from the hip flexor and lumbar extensor muscles contributes to the overall muscle fiber lengthening during the swing phase.

Contrary to our findings, several authors have found that an active warmup alone does not increase flexibility.[29,38,39] Despite concluding that static stretching with or without an active warmup increases flexibility, de Weijer et al[29] reported that participants engaging in 10 minutes of an active stair-climbing warmup alone did not demonstrate increased flexibility at any of 5 poststretch measurements in the next 24 hours. Although this appears to be a reasonable warmup, it probably does not require as much hamstring lengthening as a running warmup does. Therefore, this type of warmup might not increase flexibility. Zakas et al[38] found that adolescent soccer players who completed a 20-minute jogging warmup experienced increased flexibility only for ankle dorsiflexion. Magnusson et al[39] also observed no increase in passive knee extension flexibility after a 10-minute treadmill warmup and 30 minutes of running. Because our participants ran for less time, fatigue might have been a greater factor in previous studies, which also probably would change running kinematics.[57] Because kinematics have been shown to change with fatigue,[57] we cannot assume that the participants in previous investigations[38,39] maintained kinematics consistent with lengthening the hamstring muscle group as our participants probably did.

Despite previous research demonstrating otherwise,[29,38,39] we predict that the active running warmup before data collection was the most influential factor. First, participants across all groups demonstrated increased flexibility. Because only the intervention group participated in a stretching protocol, the 3 SLR hamstring stretches probably did not affect hamstring flexibility. Second, we believe that flexibility testing did not pose a noteworthy influence on flexibility because the position for SLR pretesting and posttesting was held for a minimal amount of time. Bandy and Irion[21] found that participants stretching for 15 seconds, 5 times per week for 6 weeks, did not exhibit an increase in hamstring flexibility. Given that they found no difference after conducting their protocol over a longer period,[21] our SLR test and retest protocol probably were not factors in increased flexibility. Third, we used a moderate-intensity treadmill speed that lasted a shorter time than that used by other investigators,[29,38,39] limiting the effects of fatigue.[57] Fourth, previous investigators[29] have stated that increased muscle length appears to be related more to the physical application of tension and not to thermal responses of the tissue to exercise. Therefore, it is reasonable to conclude that people who use a running warmup rather than stair climbing probably would see a greater increase in hamstring muscle length during and after the warmup.

Although the same examiner performed hip flexion ROM testing, we did not collect data to analyze intrarater reliability scores specific to our investigation. Because we lack evidence to establish the reliability of the examiner's hip flexion ROM measurements, variations among participants and pretest and posttest measurements might have occurred and affected the results of our research. However, Alricsson and Werner[58] reported that hip flexion ROM with the knee extended has good reliability. Therefore, we do not believe our lack of reliability testing influenced our results.

Treadmill Speed

Time was a factor in treadmill speed between the prestretch and poststretch running sessions. Participants ran 2.9 ± 0.5 m/s during the prestretch running session and 3.1 ± 0.5 m/s during the poststretch running session. Researchers have found that kinematic angles, such as anterior pelvic tilt[59,60] and hip flexion,[42,61] increase with gait speed. Because our kinematic results did not demonstrate an increase, we do not believe the change in treadmill speed between the prestretch and poststretch tests has any effect on our results.

Maximum Hip Flexion

In our study, pelvic tilt at maximum hip flexion was $6.2° \pm 5.8°$ during the prestretch running session and $6.6° \pm 5.0°$ during the poststretch running session. Schache et al[59] found that the pelvis oscillates between 15° and 20°. Schache et al[62] noted that participants running at 4.0 m/s also exhibited this trait. Treadmill speed is a likely factor for our participants exhibiting less anterior pelvic tilt because the mean anterior pelvic tilt increases slightly with speed.[59,60]

Maximum hip flexion demonstrated in our investigation was $31.7° \pm 5.8°$ during the prestretch running session and $32.1° \pm 5.8°$ during the poststretch running session. This is similar to the $29° \pm 5°$ of maximum hip flexion that has been established for recreational athletes running at a similar self-selected pace (2.95 m/s).[63] Collegiate male athletes running at a faster pace (9.0 m/s) have demonstrated a maximum hip flexion of $46.2° \pm 9.4°$.[64] Like anterior pelvic tilt,[59,60] hip flexion has been shown to increase with running speed.[42,61] Our participants did not run at a speed as high as participants in other studies,[61,64] which might explain why hip flexion in our study was less than in other studies. Another factor is the definition of *hip flexion-extension;* Swanson and Caldwell[64] defined it as the angle formed by the thigh segment in relation to the trunk, whereas we defined it in relation to the pelvis. The 2 definitions might account for some of the difference in maximum hip flexion joint angles. Although the participants in our investigation and that of Pink et al[63] did not exhibit this much hip flexion, we both included male and female recreational athletes, yet Swanson and Caldwell[64] included only collegiate male athletes. Considering the difference in populations investigated, running speed, and measurement methods, this probably is a normal and expected difference. Because our participants and those in the study by Pink et al[63] exhibited less maximum hip flexion than those in the study by Swanson and Caldwell,[64] participants in the latter study probably experienced greater knee extension and therefore a longer step length.[42,43]

The knee extension that our participants demonstrated at maximum hip flexion during the swing phase of running was $99.7° \pm 11.9°$ during the prestretch running session and $98.1° \pm 13.8°$ during the poststretch running session. This magnitude is smaller than the $111° \pm 13°$ that has been established in recreational athletes running at a similar speed.[63] Because our participants ran on a treadmill, some consciously or unconsciously might have restricted their knee extension to avoid kicking the front of the treadmill. Hamstring flexibility was not included by Pink et al,[63] so comparing the effects of stretching on that variable is difficult. However, we believe we can hypothesize that participants who experience an increase in hamstring flexibility would see knee extension angles more similar to those that Pink et al[63] observed. Because the participants' activities before data collection in the study by Pink et al[63] are unknown, we cannot determine whether they were permitted an active warmup or preactivity stretch. We also do not know how much time elapsed between the 2 running sessions of data collection. These factors could account for the difference we observed in knee extension at maximum hip flexion.

Maximum Knee Extension

Pelvic tilt measured at maximum knee extension had a main effect of sex. Men exhibited $9.5° \pm 4.9°$, and women exhibited only $3.2° \pm 1.2°$ ($P = .001$). In standing and at maximum hip flexion, the effect of sex was not different (P values = .09 and .01, respectively). Contrary to the results of our investigation, female participants have been found to have greater anterior pelvic tilt while running and standing than male participants.[62] Researchers also have found that both male and female participants have greater anterior pelvic tilt in running[62] and standing[44,45,62,65] postures than the participants in our investigation had. Given the differences previously exhibited in pelvic tilt during running, Schache et al[62] concluded that caution should be taken when averaging male and female values for pelvic tilt. This caution seems appropriate because we also found pelvic tilt values to be different in men and women. A possible explanation for the difference between men and women is forward flexion of the lumbar spine. If men increased forward trunk lean slightly from their standing positions, as expected,[47] anterior tilt would increase.[45,47] If women ran more upright with slightly decreased lumbar flexion from their standing position, the pelvis would rotate posteriorly.[44,45,47,66] However, we did not evaluate lumbar or trunk movement, so we cannot confirm this hypothesis. In addition, Sim et al[66] showed that functional hamstring to quadriceps strength ratios decrease as knee extension increases. This functional ratio compares the lengthening[41] strength of hamstrings with the shortening[41] strength of the quadriceps muscles, which commonly occurs during the running swing phase.[67] Because women have less hamstring and quadriceps strength than men,[68] the assumption that men more effectively maintain pelvic stability at maximum knee extension during running is logical.

In our study, hip flexion demonstrated at maximum knee extension was 22.1° ± 5.0° during the prestretch running session and 22.1° ± 5.6° during the poststretch running session. These measurements are larger than the 16° ± 4° that has been established in recreational athletes running at a similar speed.[63] The mean age of the recreational athletes in the study by Pink et al[63] was 32 years, whereas the mean age of recreational athletes observed in our study was 21.3 ± 1.8 years. Researchers studying walking gait have shown that as age increases, hip flexion tends to decrease.[69] Therefore, younger athletes probably will demonstrate greater hip flexion, which is associated with greater knee extension and a longer step length.[42,43] In addition, the greater hip flexion at this point in the late swing phase presented in our study probably aided in a relative lengthening of the biceps femoris and semitendinosus during running[55] that was not present in the study by Pink et al.[63] The greater hamstring length of our participants also might have aided in available hip flexion.

Our participants demonstrated maximum knee extension of 170.0° ± 4.8° during the prestretch running session and 168.7° ± 6.3° during the poststretch running session. This finding is similar to that of recreational athletes, who exhibited 170° ± 5° of maximum knee extension during the late swing phase in the study by Pink et al.[63] Swanson and Caldwell[64] observed that male collegiate athletes had less maximum knee extension (134.1° ± 7.2°) despite running at a faster speed and having greater maximum hip flexion. This result does not support the findings of other authors that greater hip flexion is associated with greater knee extension.[42,43] Late swing has been identified as the phase that induces the greatest hamstring muscle length.[55] Variations in hip flexion and knee extension during this phase also will lead to differences in the length of the hamstring muscle achieved. Recreational athletes in the study by Pink et al[63] exhibited less hip flexion, but their knee extension was comparable with that in our participants. Because our participants demonstrated greater hip flexion, a longer step length and therefore a greater peak hamstring length probably occurred.[55] Given this, we believe that hamstring tightness is a limiting factor during the late swing phase of running.[55] Because Swanson and Caldwell[64] did not measure hip flexion at the time of maximum knee extension, a comparison of probable hamstring lengthening cannot be made.

Practical Implications

Athletes with substantial hamstring tightness are not likely to exhibit typical gait patterns during the middle and late swing phases of running.[48] During fast running, they might be able to achieve hip flexion that is typical; however, the hamstring muscle length achieved probably will be offset by a subsequent increase in knee flexion.[42,43,55] When hamstrings with decreased flexibility pull inferiorly on the posterior pelvis, lumbar spine lordosis consequently decreases.[46,47,64] Lumbar extensor muscles react in an attempt to increase lordosis.[64] As fatigue from maintaining this posture occurs, forward trunk lean increases,[46] which has been associated with chronic low back pain.[47] In addition, activation of the quadriceps probably will increase as an adaptation to overcome the decreased knee extension ROM, which has been associated with patellar tendinitis[48] and patellofemoral syndrome.[49] Therefore, athletes who exhibit symptoms associated with hamstring tightness need to attempt to maintain an acceptable amount of hamstring flexibility so that normal running gait kinematics can be preserved. In athletes with notably less-than-standard hamstring flexibility, we would expect to see less maximum hip flexion and therefore shorter step length.[42,43] We would expect to see those kinematic variables increase after a stretching protocol such as ours. Changes in kinematic data might be exhibited by participants who have substantial hamstring tightness and who demonstrate increased hamstring flexibility after a stretching protocol.

Athletes without symptoms or gait compensations relating to hamstring tightness might not need to engage in single sessions of preparticipation stretching. Asymptomatic athletes relying on multiple repetitive high-power outputs or single outputs for maximal power[6] might want to reconsider engaging in preparticipation stretching because our results indicated greater hamstring flexibility in participants who did not engage in the SLR protocol and because other researchers have reported decreased stiffness[8] and maximal force production[11,13] for up to 2 hours after a stretching session.[11] On the other hand, asymptomatic athletes engaging in high-frequency, stretch-shortening cycles at a low percentage of the maximum probably can engage in a moderate-intensity active running warmup similar to their sport activities with or without stretching according to their comfort because swing-phase kinematics do not appear to change in response to a static SLR stretching protocol.

Limitations

Our study had several limitations that should be considered when one interprets the results. First, the stretching protocol used did not produce more hamstring flexibility than a warmup alone, which makes testing our initial hypothesis difficult. It is probable that the subjective aspects of this protocol are related to these results. However, given that athletes commonly complete 3 SLR stretches for 30 seconds with a partner in practice, we reasoned that using the same protocol in this investigation would be fitting.

Second, we studied healthy recreational athletes who were not necessarily runners. We chose healthy participants to avoid including participants with injuries related to their limited hamstring flexibility. Therefore, investigating the effects of hamstring length on the running kinematics in avid runners or in populations with insufficiencies in hamstring length or orthopaedic injuries might produce different results. Third, we did not specifically investigate multiple joint kinematics.

CONCLUSIONS

Our results suggested that a single session of 3 hamstring stretches did not change pelvis, hip, or knee kinematics during running. The increase in hamstring length experienced by both groups probably resulted from an active warmup and not from the stretching protocol that intervention participants experienced. Our results are attributed to a healthy population of recreational athletes. Therefore, our results and conclusions pertain to such a population. To gain more insight into these results and expand on the populations to which they pertain, future research should involve a larger number of participants, including those with substantial hamstring tightness and associated altered running kinematics. Including multiple joint kinematics would yield a more complete examination of the possibility of kinematic changes after a stretching protocol. Therefore, single- and multiple-joint kinematics should be investigated, especially in combination with a stretching protocol. This would add perspective to the effect of the hamstring muscle group on the kinetic chain during running. In addition, the effects of a chronic hamstring stretching protocol on running kinematics could be assessed.

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